1 Introduction

The emergence and rapid proliferation of wireless telephony and broadband service have introduced the most dramatic transformations in the telecommunication industry since the invention of the telephone in 1876. When Ameritech first introduced cellular service in the United States in 1983, however, few would have imagined its explosive growth potential. After all, the first wireless phones were large, weighing over two pounds each, and airtime prices were nearly $1 per minute.[1] Yet by 2012, the technology had improved significantly and the prices of wireless handsets and subscription services had fallen dramatically. The result: over 300 million wireless subscribers in the U.S. and roughly 6 billion wireless subscribers worldwide.[2] Over 40 percent of all U.S. households today are wireless-only.[3]

The rapid pace of consumer demand, technology and public policy changes in this industry has raised a number of important questions that economists have only recently begun to address. Prominent among these questions is how the presence of wireless telephony affects households' choices as they seek to have their communications needs met. Insights into this question promise, in turn, to shed light on a number of current economic policy questions, including whether wireline and wireless services are better described as complements or substitutes, whether traditional public policy efforts to promote wireline subscription to the public switched network are necessary in light of the rapid wireless services adoption, and whether competition between wireline and wireless platforms is sufficient to warrant a "light-handed" approach to industry regulation. Additionally, the emergence of wireless technologies raises broader questions regarding the potential for improved efficiencies in specific industries, such as health care, education, insurance, agriculture and fishing, as well as to the broader economy.[4]

Two streams of economic research have emerged which provide some assistance in addressing the issue of household telephony choices in an environment that includes wireline and wireless options. The first is a rich literature on the demand for wireline telecommunications.[5] The second is a more recent literature on the diffusion of wireless telephony.[6] While

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[1] Mayo and Woroch (2010).

[2] International Telecommunication Union (2012).

[3] See Blumberg and Luke (2013). Following their terminology, we refer to "wireless" as what alternatively is termed "mobile", "cell", or "cellular" service.

[4] For industry-based studies of the impact of advanced telecommunications, see, e.g., Brown and Goolsbee (2002), Jensen (2007) and Aker (2010). See Röller and Waverman (2001) for a study of the macroeconomic consequences of the deployment of advanced telecommunications.

[5] For a detailed review, see Taylor (2002).

[6] Vogelsang (2010) provides a thorough review of the diffusion of wireless telephony, including studies using microdata from the early 2000s that seek to estimate evidence of consumer substitution across fixed (wired) and mobile (wireless) services. See, e.g., Rodini, Ward and Woroch (2003) and Ward and Woroch (2010). For a literature survey of economic issues related to the wireless telephone industry, see Gans, King and Wright (2005).

both research streams are informative, neither captures the rich evolution of consumers' decisions regarding their telecommunications portfolios over the past decade. In particular, given the dramatic evolution of wireline and wireless services, natural questions arise regarding the economic motivations driving adoption when consumers now have multiple options to satisfy their communications needs, including wireline service only, wireless service only, both wireline and wireless services, and neither wireline nor wireless service.

In this paper, we take a step toward understanding the evolution of telecommunications demand in the context of an environment in which consumers face a portfolio choice. We do so by first developing a simple model of household choice for alternative platforms that satisfy their communications needs. One alternative is a high quality wireline platform that provides telecommunications services between wired nodes, but is incapable of providing communications for consumers who are not physically located at such nodes. Another choice is (initially) a lower quality wireless platform, but offers consumers the ability to communicate while away from the wired nodes. Other household choices include the selection of both platforms or neither platform. Our model provides insights into the household and network characteristics that are likely to arise as key determinants of the choices that households make regarding how to satisfy their communications needs. We also explore conceptually the implications and interpretations of consumer patterns of substitution across platforms in the face of alternative prices. This approach allows us to frame an empirical analysis that explores both non-price and price determinants of demand, including the substitutability or complementarity of wireline and wireless services.

Given this model, we then draw upon a large and unique survey of household-level communications platform choices over 2003-2010 to empirically model households' decisions to adopt wireline services, wireless services, both services, or neither service. The estimations provide consistent support for the conceptual framework. In particular, households whose characteristics indicate greater spatial mobility of household members are significantly more likely to gravitate toward portfolio choices that include wireless telephone service. And conversely, households whose characteristics signify greater attachment to their homes are more attracted to wireline telephone service. Our empirical analysis also provides strong evidence that wireless telephony has become a close substitute for wireline telephony over the 2003-2010 period.

2 A Model of Consumer Choice in a Wired and Wireless Environment

2.1 Substitution Patterns: Nonprice Considerations

Consumers' demand for telecommunications services is a consequence of the desire both to be able to transfer information (i.e., voice, data or video) to others and to be able to receive information from others when sufficiently spatially separated to make direct communications difficult. Historically, telecommunications has been available only at fixed (wireline) nodes, so telephone calls from one consumer to another were characterized by exact physical locations. Within this context, models of telephony demand emerged in the 1970s. Over time these models have sought, for example, to capture the essence of network externalities [e.g., Rohlfs (1974)], to model consumer demand in the presence of multiple nonlinear pricing options [e.g., Train, McFadden and Ben-Akiva (1987)], and to model the role that local and long-distance service boundaries and pricing play on telecommunications demand [e.g., Martins-Filho and Mayo (1993)].

While advancing understanding of the demand for traditional telephone services, these models have not typically allowed for consumer preferences to reflect a desire (or an ability) to communicate away from fixed nodes. The emergence of wireless telephony, however, provides the opportunity for a broader description of consumer demand. In particular, while a consumer may retain the demand for wireline communications, she may also gain utility from being able to reach other consumers who are not at a wireline node. Similarly, a consumer may also gain utility from the ability of another consumer to reach her while she is away from her node.[7]

That is, communications demand was driven by the utility of a consumer i, located at her node, to communicate with another consumer j, $j = 1 \ldots m$, located at her node, by either making or receiving telephone calls between i and j.[8] The emergence of wireless telephony, however, provides the opportunity for a broader description of consumer demand. In particular, while consumers may retain the demand for N_i to N_j communications, they may also gain utility from being able to reach other consumers who are not at a wireline node. Similarly, a consumer i may also gain utility from the ability of another consumer j to reach her while she is away from her node.[9]

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[7]It is also possible that wireless service may not only afford mobility, but also enhance communications services breadth. This would happen, for instance, if wireline broadband service was unavailable while broadband service was available via wireless technologies.

[8]Of course, households also may place value on the option to make or receive calls between nodes.

[9]It is also possible that wireless service may not only afford mobility, but also enhance communications services breadth. This would happen, for instance, if wireline broadband service was unavailable while broadband service was available via wireless technologies.

Thus, consider a household with $N = \{1, ..., n\}$ members. Each household member n_i has a "community of interest" consisting of $M_{ik} = \{m_{i1}, m_{i2}, ..., m_{ik}\}$ other non-family members. At any moment in time, a household member i may get the urge to communicate with family member j or a member of her community of interest m_{ij}.[10] This urge occurs randomly and independently of a person's subscription decisions and her present location (at home or away). For simplicity, suppose that communications between person i and other family members and members of the community of interest are undifferentiated, so we allow j to index both household members and community of interest members. If i is able to connect with j she derives utility u_{ij}. As the receiver will also be affected by the call, let v_{ji} be the utility to j if she is called by i. It is reasonable to assume the caller has more to gain than the receiver (*i.e.*, $u_{ij} > v_{ji}$) if only because the caller was incited to initiate the call before the receiver did so. In fact, the receiver may not want calls from certain callers (e.g., telemarketers) in which case $v_{ji} < 0$. The utilities to both the caller and receiver are assumed to vary depending on the quality of the wireless connection relative to calls made using a landline telephone (which is the assumed default).

We further assume that individual i is at home with probability ϕ_i and away from home with complementary probability $[1 - \phi_i]$. Wireless telephony service is equally available at home or away but not with perfect certainty or high quality. For instance, the cellular network may be unable to establish a connection in the user's location either because of carrier coverage area gaps or because of carrier signal weakness (as when a user is in a building). Let λ_i be a quality variable, measuring the probability that individual i connected to a mobile carrier's network and is successfully able to place and receive mobile calls. The size of λ_i will depend, among other factors, on the capacity of the local wireless network. Finally, we assume that individuals while at home utilize their landline telephone for calling family members and members of their community of interest.

Thus, the utility of i in a wireline-only world can be fully characterized by:

$$\mu_i = \sum_j \phi_i \phi_j (u_{ij} + v_{ij}). \tag{1}$$

Allowing for the possibility of wireless communications, we can now represent a consumer i's utility from telecommunications services more fully by:

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[10]We abstract from the role that prices may play in rationing calling intensity. Specifically, because most wireless subscriptions are for "buckets" of minutes, the marginal price of an additional call is zero unless the subscriber has exhausted the minutes allotted in the bucket. We thus consider the effective marginal price of usage to be zero so that every urge to call is unconstrained by price.

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$$\mu_i = \sum_j \phi_i\phi_j(u_{ij} + v_{ij}) + \sum_j [1 - \phi_i]\lambda_i\phi_j(u_{ij} + v_{ij}) +$$
$$+ \sum_j \phi_i[1 - \phi_j]\lambda_j(u_{ij} + v_{ij}) + \sum_j [1 - \phi_i]\lambda_i[1 - \phi_j]\lambda_j(u_{ij} + v_{ij}),\,[11] \tag{2}$$

where $j = 1, ..., n + k - 1$.

Equation (2) represents the utility to i of all i to j communications, which is the sum of the utilities (1) from i's wireline to j's wireline; (2) from i's wireless to j's wireline; (3) from i's wireline to j's wireless; and (4) from i's wireless to j's wireless, respectively. Note, that if i does not have a landline, it is equivalent to $\phi_i = 0$; if i is not subscribed to a wireless service it is equivalent to $\lambda_i = 0$.

This specification highlights several salient features that we capture in our empirical analysis. First, equation (2) points to an important role of the mobility of both i and j in the realization of i's utility from wireless service subscription. For instance, note that as ϕ_i approaches 0, the value of the first and third expressions in equation (2) approach zero, respectively. That is, the ability of i to realize utility from communications with j while i is away from her home is contingent upon having a mobile subscription. Alternatively stated, the value of mobile subscriptions will increase the greater the likelihood that i and j are away from their home. If, on the contrary, ϕ_i is rather big, the value of the second and forth expressions in equation (2) approach zero. In other words, if i spends the majority of her time at her node, subscription to mobile service might not add extra value to i's utility.

Second, note that in the event j is not subscribed to a wireless service ($\lambda_j = 0$) it effectively eliminates the latter two terms in equation (1). If household member i particularly values communication with j and ϕ_j is low the marginal utility to i from j's subscription to a mobile service may therefore lead to inter-personal "side-payments" to support j's subscription even when, absent those payments, j would chose not to subscribe to a mobile service. Such side-payments are most frequent between family members. The value of λ_j also highlights a more general network externality effect. Specifically, the value to i of wireless subscription will depend on the ability to communicate with members of her family and community of interest even while those members are away from a landline telephone, thus making the value to i contingent upon j's subscription to the wireless network.

Finally, Equation (2) makes it apparent that variations in λ_i and λ_j, reflecting the quality

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[11] We follow the convention first established by Rohlfs (1974, p. 20) in assuming that interrelationships between the demand for telecommunications services and other non-communications services purchased by consumers can be ignored. Similarly, we eschew (for the moment) a discussion of the effects of pricing on consumption patterns. We return to this below, however, in Section 2.2.

of the wireless networks subscribed to by i and j will affect i's utility from subscription to a wireless network. Lower values of λ_i and λ_j make it less likely, *ceteris paribus*, that i will find it in her interest to subscribe to a mobile network.

To summarize, for consumer i, the incremental utility associated with subscribing to wireless service depends on: (a) whether consumer i has a demand to communicate with other consumers ($j = 1 \ldots n + k - 1$) while i is away from her node; (b) the probability of consumer i being at her node at the time that i to j communications is desired;[12] (c) the ubiquity of wireless coverage; (d) the quality of wireless service relative to wireline service; (e) the network effect created by others' subscriptions to the telephone network; and, (f) the utility to consumer i of being reachable by the other consumers j when i is away from his node. Our empirical model will seek to capture these demand drivers.

2.2 Substitution Patterns: Price Considerations

Turning to the effects of pricing on consumer demand, our goal is to determine the economic relationship between wireline services and wireless services. In particular, we seek to determine whether access to wireless service serves as a complement to, or substitute for, access to wireline service. As such, the central questions are ones of consumers' responsiveness to price changes in nodal wireline services (N) and wireless services (W).[13] Wireline telephone service is typically priced as a lump-sum monthly payment with a zero marginal

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[12]We abstract away from the potential for households to gain utility from asynchronous communications such as voicemail, email, video and file transmissions that are not received simultaneously. We also implicitly assume that the wireless device is "turned on" while individuals are away from their nodes rather than receiving a message and subsequently returning the call at a later time. Incorporating these considerations would involve discounting the utility from fully contemporaneous communications without any harm to the basic approach we adopt here. We also abstract away from the distinction between the called party being at her node from the called party being at any wired node. In our empirical analysis, however, we account separately for these possibilities.

[13]Our approach here shares a nomenclature with an independent literature in economic strategy that seeks to determine whether particular corporate strategies are substitutes or complements. For example, Braga and Wilmore (1991) examine the issue of the relationship of technological imports and in-house R&D efforts. Within this literature, key insights into questions of substitutability or complementarity are seen to arise from either observed positive or negative correlations in measures of the strategies themselves or in the errors of reduced-form regressions of the strategies. This approach has developed and been refined over the years by a number of contributions, including Milgrom and Roberts (1990), Arora and Gambardella (1990), Arora (1996), Athey and Stern (1998) Miravete and Pernias (2010), and Kretschmer, Miravete, and Pernas (2012). As noted by Arora (1996), this approach is necesitated by the absence of the 'price' of adopting particular strategies. Gentzkow (2007) extends this literature and builds explicit linkages between this general approach and the conventional approach toward substitutability/complementarity issues when price variation is unobserved. Fortunately, as described below, we are able to directly capture price variations across consumers for the various portfolio alternatives and are able to observe consumer reactions to those price variations. In this manner, our approach is more conventionally set within the standard microeconomic assessment of substitutability/complementarity based on observed consumer reactions to alternative prices.

price per minute of use.[14] Similarly, wireless telephone service pricing plans most typically incorporate allowances for a number of minutes that have a zero marginal price as long as the consumer's usage does not exceed the allowance. In these circumstances, the consumer's subscription will depend on a comparison of the monthly subscription fees of wireline and wireless services to the amount of consumer surplus enjoyed from wireline and wireless usage, after consumers have paid their respective monthly fixed charges.[15]

Let P_N represent the prevailing price of wireline telephone service in the household; and let P_{Wi} represent the prevailing price of wireless service for household member i. Individual households maximize the utility gained from wireline and/or wireless communications relative to the cost of these services for all household members:

$$\max\{\sum_i (\mu_i - P_{Wi}) - P_N\} \tag{3}$$

Based on the household's maximization problem stated by equation (3) we can estimate the probability of each household to subscribe to (1) no telephone (π_0), (2) wireline service (π_N), (3) wireless service (π_W), or (4) both wireline and wireless services (π_{NW}).

To generate insights into the degree of substitutability or complementarity of consumers' demand for wireline and wireless services we explore how the probabilities of subscription are affected by variation in the prices of wireline and wireless services. In this regard, we focus on the (subscription-based) quantities of wireline services ($Q_N = \pi_N + \pi_{NW}$) and wireless services ($Q_W = \pi_W + \pi_{NW}$). We can then define the economic relationship between nodal wireline and wireless services as:

$$\frac{\partial Q_W}{\partial P_N} = 0 - \text{Wireline and wireless services are independent,}$$

$$\frac{\partial Q_W}{\partial P_N} > 0 - \text{Wireline and wireless services are substitutes,}$$

$$\frac{\partial Q_W}{\partial P_N} < 0 - \text{Wireline and wireless services are complements.} \tag{4}$$

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[14]We set aside here the *de minimis* portion of consumers who subscribe to local wireline telephone service on a usage basis.

[15]See Taylor (2002).

3 Empirical Setting and Data

To estimate consumer decisions regarding their portfolio of telecommunications choices, we begin with a unique micro-level database assembled by the National Center for Health Statistics (NCHS), which operates as part of the Centers for Disease Control (CDC). NCHS administers the National Health Interview Survey (NHIS) annually as the principal source of information on the health of the U.S. civilian non-institutionalized population. Interviewers visit households and collect data on roughly 75,000-100,000 individuals annually.[16] Our data are over the 2003-2010 period, with nearly 25,000 households surveyed each year. As shown in Appendix A, NHIS-surveyed households generally track U.S. population demographic characteristics closely.[17] Households are queried in this survey regarding their subscription to wireline and wireless telephone services. Of particular interest are questions about whether the household has no telephone, a wireline telephone only, a wireless telephone only, or a wireline telephone and (one or more) wireless telephones.

While the public use portion of the data are helpful, the specific locations of surveyed households remain confidential. By application to and approval from the NCHS, we gained access to the confidential household data maintained at a secure facility in Hyattsville, Maryland. Using household-level geocodes, we are able to link the NHIS survey data to location-specific data from several public data sources, including the Federal Communications Commission, the United States Census Bureau, the United States Bureau of Labor Statistics and the United States Department of Agriculture. We describe these other data sources below.

3.1 Data Overview and Summary Statistics

The combined dataset for empirical analysis includes 189,616 observations over the 2003-2010 period. Table 1 provides summary statistics on households' subscription to wireline and wireless services, while Figure 1 shows the evolution of households' portfolio choices over the 2003-2013 period.[18] Several characteristics of households' portfolio choices are noteworthy. First, the proportion of households not subscribed to any telephony service is small (about one percent) and remains so throughout the sample period. Second, the proportion of

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[16]For a detailed overview, see *http : //www.cdc.gov/nchs/nhis/about_nhis.htm.*

[17]To provide additional assurance that our empirical analysis is not unduly affected by the sampling methods of the NCHS, we employ the sampling weights established by CDC as a robustness check to the estimations we report in Section 4. The results we report are substantively unchanged by the application of the sample weights.

[18]The extended publicly available data for 2011-2013 are available at http://www.cdc.gov/nchs/nhis/quest_data _related_1997_forward.htm. The data shown in Figure 1 are unweighted. Weighted observations yield essential the same pattern as what is reported here.

households subscribed exclusively to wireline service decreased dramatically from roughly 49 percent in 2003 to just under 9 percent in 2013. Third, the corresponding share of households subscribing exclusively to wireless telephony grew over the sample period from roughly four percent in 2003 to nearly 42 percent in 2013. Finally, households subscribing to both services grew at the beginning of the sample period from 46 percent to a peak of 61 percent in 2007 and has subsequently declined to 47 percent in 2013.

The data also reveal important subscription pattern differences by household income. Figure 2 shows the evolution of telephone portfolio choices for households that are below the poverty thresholds in each year. By 2013, the share of poor households subscribing to wireless services only (around 57 percent) was significantly higher than the share of all households subscribing to wireless services only (around 42 percent). Similarly, by 2013 poor households subscribed in larger proportions to wireline service only (roughly 13 percent) in comparison to all households (roughly 9 percent).

Finally, the data point to important changes in telephone portfolio choices by household age. Figure 3 shows that the movement to wireless-only consumption has been particularly dramatic for young households (household members less than 31 years old) over the 2003-2013 period. In 2003, nearly 13 percent of young households subscribed exclusively to wireless services and over 85 percent subscribed to either wireline service only or both wireline and wireless services. But by 2013, over 82 percent of young households subscribed only to wireless service, while the share subscribing to wireline only had fallen to approximately one percent and the share subscribing to both services had fallen to roughly 13 percent.

3.2   Variables

Our effort to capture variations in observed household telephone portfolio choices focuses on four categories of variables. First, based on the Section 2.1 discussion, we include variables that are designed to capture the degree to which household members are affiliated more closely with their domicile (node), or alternatively are considered more mobile. Second, we incorporate measures of the respective prices of wireline and wireless telephone service, along with measures of household income. Third, we include measures that seek to capture the wireless telecommunications quality relative to the wireline network. Finally, we include measures to account for demographic characteristics of households.[19] We provide a general overview of these variables below, but a more detailed set of variable definitions and sources is provided in Appendix B.

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[19] As implied by equations (1)-(4) above, the conceptual possibility of network externalities may also drive consumer demand among telecommunications users. Because network subscription rates within our sample are very high (consistently in excess of 98 percent), we choose as a practical matter to not pursue these potential effects which are likely to be *de minimus* at subscription levels approaching 100 percent.

Nodal Variables   Several variables are included to capture the degree to which household members are more (less) closely affiliated with their nodal domicile. Because older households typically spend a greater proportion of their time at home,[20] we include several age-related variables. We first account for whether the household includes a retired individual (*Retired Household*).[21] We next account for whether the household consists solely of individuals under age 31 (*Young Household*), between ages 31 and 45 (*Young-Middle Household*), between ages 45 and 64 (*Older-Middle Household*), or over age 64 (*Older Household*). We expect that older or retired households are more closely affiliated with their node and will therefore be more prone to subscribe to wireline service than wireless service. Conversely, we expect that younger households are attracted in greater proportions to wireless service, as it enhances their abilities to communicate while being "on the go". While more mobile lifestyles among younger households may be thought to create greater attraction to wireless telephony than older households, it is also possible that older consumers are leary of "new" technologies, and will remain loyal to wireline telephony longer than younger households. To allow for this potential, we also account for whether an older household is also wealthy (*Wealthy Retired Household*).[22] We expect that wealthier elderly households are more mobile and less intimidated by new technologies, thereby enhancing wireless telephony subscription.

We also account for household nodal demographics by including measures of whether the household has children (*Children*) and whether any children are students (*Student*). Our expectation is that parents place high priority on "anywhere, anytime" communications with children and students, and will accordingly have enhanced demand for wireless services relative to households without children and students. At the same time, children and students create greater attachment to the family domicile, so we also expect that children and students will create a greater propensity for the household to subscribe to wireline service.

A unique feature of our data is that it includes measures of the health of household members. To take advantage of this information, we account for potential health-related impacts on households' telephone portfolio choices. In particular, we account for households that have a health-impaired youth (*Limited Youth*) or health-impaired adult (*Limited Adult*). Our expectation for the former is that such households have a greater demand for "anywhere, anytime" communication and are therefore more inclined to include wireless telephony in their portfolio, while our expectation for the latter is that such households have a stronger nodal presence and corresponding need for wireline service.

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[20]Bureau of Labor Statistics (2011).

[21]We alternatively substituted this variable with one that accounted for whether the surveyed household included a member that draws Social Security benefits. There was virtually no change in the subsequent empirical results.

[22]In an alternative specification, we accounted for the education level of the primary respondent in the retired home. The results are similar to those that we report below.

We also account for the working status of the household via several variables. We first account for the ratio of household members employed outside the home (*Ratio Working*). We suggest that work-related matters take household members away from their domicile, making nodal wireline service less attractive and wireless service more attractive. We also account for whether any household member is employed part-time *(Part-time Employed)*. Given the mobile nature of such households, we expect that part-time employment is associated with an enhanced propensity to subscribe to wireless service. But a household member that is only employed part-time signals greater attachment to the domicile, and therefore likely enhances wireline service demand. We also account for whether a member of the household has self-identified as a housewife (*Housewife*) to examine whether this creates a greater nodal presence and, hence, attraction to wireline services.

Given the efficiency gains from the wider reach [c.f., Jensen(2007)] and the security benefits of mobile telephony in rural areas, we include a measure of the degree to which the household is located in more sparsely populated areas. In particular, we include a variable to capture the population density of the county within which the household resides (*Population Density*). We expect that for a given wireless infrastructure quality level, the propensity of rural households to subscribe to wireless telephony will be enhanced.

Finally, we account for domicile ownership using an indicator variable that differentiates between households that own their home versus rent (*Own House*). Our expectation is that ownership signals greater nodal attachment, with a corresponding increase in the propensity toward wireline telephony services.

Price and Income Variables   Prices are at the heart of demand theory. Accordingly, we include measures of the individual prices of wireline and wireless services. To capture variations in wireline service prices, we begin with 2002 data on the basic flat monthly charges by wire center throughout the U.S.[23] Because the areas served by wire centers are not typically contiguous with county boundaries, we use population weights within individual wire centers to construct a weighted price by county for residential landline service throughout the U.S. To update these data for the larger sample period, we utilize the Federal Communication Commission's (FCC) "Reference Book of Rates, Price Indices, and Household Expenditures for Telephone Service" (Reference Book). In particular, the Reference Book reports the results of an annual survey of local monthly fixed telephone rates for 95 cities throughout

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[23]These data were graciously provided to us by Greg Rosston, Scott Savage and Bradley Wimmer. See Rosston, Savage and Wimmer (2008) for a detailed description. While many local telephone companies offer local measured service in which customers pay a smaller monthly subscription charge and (after a call or minute allowance) pay a marginal charge per minute or call, industry sources report that the percentage of customers who avail themselves of this option is *de minimus*. Accordingly, we focus on consumers' choices based on variations in flat monthly rates.

the U.S. The year-to-year values of Pearson correlations for prices in these cities are very high, averaging .96 across for the relevant time period, indicating that the principal source of wireline rate variation is captured by our spatial disaggregation of prices at the sample period beginning. Accordingly, *Wireline Price* is updated by the values of Consumer Price Index (CPI) for local exchange service for the 2003-2010 period.[24]

We also include the price of wireless telephone service subscription. While numerous wireless subscription plans exist, they most generally entail a flat rate charge for a "bucket" of minutes.[25] For consumers whose usage levels remain within the purchased bucket, the price can be taken as the average monthly expenditure for the service.[26] Data on the average monthly revenue per user (including roaming charges and long distance toll calling) were provided to us by the Cellular Telephone and Internet Association (CTIA). We rely upon *Wireless Industry Indices*, a semi-annual survey conducted by CTIA of its member companies. In the survey, data were received by companies representing over 95 percent of all U.S. wireless subscribers, and are provided for the 2003-2010 period. While wireless prices are typically geographically invariant, state and local taxes impose spatial variations in the prices paid by consumers in different locales. To capture these variations, we incorporate state and local tax data provided by the Committee on State Taxation (COST). The data are derived from a series of studies conducted by COST, beginning in 1999 and repeated thereafter every three years (i.e., 2001, 2004, 2007 and 2010),[27] which report the prevailing state sales tax rate inclusive of general sales taxes. Local tax rates for each state were taken to be the average between those imposed in the largest city and the capital city. Federal taxes were reported separately. Any flat fees (e.g., 911, Universal Service Fund) were converted to percentages based on average monthly residential bills. In the first two reports, a single tax rate was provided that blended the state and local taxes applied to wireline local and long distance service, and mobile service. In later reports, taxes levied specifically on wireless service were reported separately. After incorporating state and local taxation

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[24]Robustness checks of our estimations that employed alternative price measures, such as measures of annual telephone CPI variations or CPI ratios for local and wireless telephone service, gave results that are very similar to those reported below.

[25]Our price measurement captures the fact that the prices of calling from a wireless or wireline telephone are invariant to the type of telephone being called. While the price for wireless calling is generally invariant to the identity of the carrier of the customer being called, during the timeframe of our data, a few plans involved differentially lower prices for consumers making calls to subscribers of the same wireless provider. We are unable to capture this variation.

[26]Because there are numerous wireless carriers offering service in the United States, each with a number of wireless pricing plans, our measure of the price of wireless service is a composite measure of these plans. While it would be ideal to access individual firms pricing plans and to yoke this information with subscription decisions of the individual households in our database, this level of granularity is unavailable. Accordingly, our measure necessarily glosses over the ability of households to endogenously adopt one pricing plan, or firm, over another.

[27]See COST (1999, 2002a, 2002b, 2005a, 2005b) and Mackey (2008, 2011).

variations, our measure of *Wireless Price* entails both spatial and inter-temporal dimensions over the relevant period.[28]

As is common in modern demand estimation, we consider the potential endogeneity of prices which in our case may most directly be thought to arise either from omission of relevant exogenous variables (or product characteristics) or from a causal feedback from observed demand on prices. In the case at hand, however, potential endogeneity concerns are tempered somewhat by two considerations. First, while a common source of endogeneity bias arises from the omission of relevant independent variables, our model includes a wide-ranging and substantial number of explanatory variables that may reasonably be thought to collectively mitigate this source of endogeneity bias. Second, in our case, feedback from observed demand on prices is mitigated by the particular price-setting mechanisms in the telecommunications industry. Specifically, wireline prices are determined by the regulatory process, which in large part is driven by supply-side (cost) considerations. This is most obviously true for traditional rate-base/rate-of-return regulation. It is also true, however, for price cap regulated firms, whose initial prices under price cap regulation were most often set by existing rates that were established under rate-of-return regulation. Subsequent price changes under price cap regulation have most typically been driven by changes in measures of general inflation (e.g., the CPI) and productivity changes, neither of which tend to be driven by market demand. Similarly, geographic variations in the price of wireless telephony are captured by variations in state and local tax differences, which are, again, not driven in any obvious way by market demand and are exogenous to the carriers. While these considerations help ameliorate endogeneity concerns, as described below we nonetheless incorporate econometric methods based on Rivers and Vuong (1988) and Petrin and Train (2010) to assure the integrity of the parameter estimates and their corresponding statistics.

Drawing on the NHIS survey data, we also include measures of household income. Household income is categorized relative to an annual poverty threshold using four dichotomous variables. Household income below the poverty threshold (*Income1*), between one and two times the poverty threshold (*Income2*), between two and four times the poverty threshold (*Income3*), and more than four times the poverty threshold (*Income4*) are relevant categories.

Quality and Network Effects Variables Consistent with Section 2, we seek to capture both intertemporal and geographic variations in the relative quality of wireline and wireless services. Given that wireline service has been engineered to very high levels with *de minimis* blocking rates over our sample timeframe, we principally focus our efforts on quality

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[28]We examined alternative constructions of the wireless price variable in the estimations reported below with essentially no substantive differences from those reported here.

variations in wireless services. Wireless service quality is affected by both topographical characteristics of the local calling area and the extent of infrastructure build-out. We accordingly gathered data from the United States Geological Survey (USGS) on the extent to which the hilliness or mountainous nature of the local terrain may impair wireless communications quality. *Mountainous* is coded on a 21 point scale ranging from flat plains (1), to open low hills (13), and to high mountains (21). We also account for the provisional challenges of high quality wireless service poised by large bodies of water, and accordingly gathered data from the United States Department of Agriculture (USDA) to account for the percentage of the household's county that is water (*Water*).

As noted in Section 2, the quality of wireless services may suffer either from lack of geographic coverage or from insufficient capacity relative to demand (leading to dropped calls). Wireless industry infrastructure grew significantly over the 2003-2010 period, with corresponding increases in the ubiquity of coverage and call quality. To capture this variation, we include a measure of the number of cellsites deployed over time (*Cellsites*).[29] We also account for the potential "reflection problem" identified by Manski (1993) that can arise when the average behavior in a population influences the behavior of individuals within that population. In our case, the question arises whether the observed distribution of cellphones among an individual's "community of interest" might provide a network effect as identified in equation (2). We allow, alternatively, two variables to capture any such network effect. Our broader measure is the nationwide deployment of cellsites, which serves as a proxy for the ability of an individual to reach other mobile subscribers. A more narrow measure, in the spirit of Goolsbee and Klenow (2002) is the number of cellphone subscribers within the Economic Area of the household.

Finally technological changes over the past decade have brought notable and corresponding changes to the versatility (quality) of wireline telephony. Specifically, during the first decade of the 2000s, wireline broadband was increasingly deployed across the United States. Concurrent with the deployment of wireline broadband, providers of both telephone service and cable television began to introduce bundled offerings of these services with high-speed

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[29]In the initial years of cellular telephony, cell sites were typically large stand-alone towers. Over time, providers have deployed quality and capacity enhancing antennae on large buildings, utility poles, water towers, etc., so that "towers" are no longer the most accurate measure of wireless capacity. We therefore draw upon a broader measure of cell sites made available by CTIA, which includes repeaters and other cell-extending devices but excludes microwave hops. Because the specific cell site locations are proprietary, we are unable to account for their geographic distribution. More recent deployments of wireless repeaters and antennae have greater coverage and capacity-enhancing characteristics than earlier vintage deployments. Also, wireless network capacity depends upon the "back-haul" capacity of cell sites which carry wireless traffic to the landline network. Increasingly, such "back-haul" is provided by high-capacity fiber which dramatically increases the ability of specific cell sites to handle larger volumes of voice, data and video traffic. Accordingly, our count of cell sites may underestimates the actual wireless capacity and quality increases over time.

internet access.[30] To account for the potential demand effects of this increased versatility of the wired connections into households, we introduce *Wireline Broadband* which measures the proportion of households within a state over time that subscribe to wireline broadband services.[31]

Demographic Variables Finally, the existing literature has identified a number of demographic characteristics that affect the likelihood that households subscribe to the "telephone" network. Riordan (2002) surveys this literature, and also independently verifies several demographic factors as contributing to households' propensities to subscribe to wireline service. We accordingly account for households' racial composition (*White, Black, Hispanic, Asian, Indian,* and *Chinese*), gender composition (*Female Household* and *Male Household*), and marital status (*Divorced*) as controls.

4 Estimation and Results

To provide a better understanding of consumers' selection of a portfolio of available telecommunications services, we first report correlations between household's subscription to wireline and wireless telephone services. The second column of Table 2 reports tetrachoric correlations for households' decisions to adopt wireless and wireline services, respectively.[32] These estimates represent simple correlations between households' decisions to adopt wireline services with their decisions to adopt wireless services (1 if "yes", 0 if "no"). The pattern of correlations is consistently negative: households that adopt wireless telephony are less likely to adopt wireline telephony ($\rho = -.53$). The observed correlations are statistically significantly different from zero at the .01 level. As seen in Table 2, moreover, this pattern of negative correlations holds not only for the entire sample of surveyed households but also within each sample year and across all income levels, with the largest negative correlations occurring in the lowest income households.

Table 2 also reports the partial correlation coefficients between wireline and wireless consumption, after controlling for a number of variables, including price, income, demographic

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[30]See Prince and Greenstein(2013)

[31]As a robustness check, we also drew directly on state-level data collected by the FCC over the 2008-2010 period on households that explicitly subscribed to wireline telephony as part of a bundled offering. The results of this alternative estimation are substantively invariant to those reported in Section 4 below, but involve sacrificing approximately 100,000 observations over the 2003-2007 period. Accordingly, we report our the estimations using *Wireline Broadband* in Section 4 below. In addition to our measure of wireline broadband, we also sought to incorporate the potential demand effects of the emergence of wireless broadband. Unfortunately both the novelty of this phenomenon and inconsistent data collection methodologies by the FCC prohibited our use of such a measure in the estimations.

[32]Tetrachoric correlations are developed for two normally distributed variables that are both expressed as dichotomous. See Greene (2012), p. 741.

variables (*Female/Male Household, Black, Divorced*), nodal variables (*Young Household, Young-Middle Household, Older-Middle Household, Children, Student, Own House, Ratio Working, Part-Time Employed, Retired Household, Wealthy Retired Household, Housewife, Limited Youth, Limited Adult, Unrelated Adults, Population Density*), and wireless telephony quality variables (*Cellsites, Water, Mountainous, Wireline Broadband*). Column 3 indicates that the relationship between wireline and wireless consumption remains negative ($\rho = -.37$) and is highly statistically significant (even after controlling for several other correlates). The negative correlations again hold not only for the entire sample but also for each year (with the exception of 2003) and income level, with the highest (negative) correlations observed at the lowest income levels.

While these simple correlations are consistent with the substitutability of wireline and wireless services, the presence of correlations of unobserved tastes and preferences across consumers may also account for these observed patterns. Consequently, it is necessary to parse out the effects of these correlations from the true substitutability or complementarity of the services in question. It is to that effort that we now turn. Our approach embodies two identification-enabling features. First, unlike Gentzkow (2007), we are able to explicitly account for consumer reactions to observed price variations. Second, our econometric approach explicitly accounts for the potential for observed correlations in the error structures for consumers who are making their telephone portfolio decisions.

To parametrically investigate the empirical relationship between wireline and wireless subscriptions, we employ several discrete choice models. In any discrete choice analysis, the first step is to identify the available choice set. For our purposes, we assume that both wireline and wireless services are in the choice set, as is the option to not subscribe to any telephone service.[33] As described in Section 2, we seek to understand the decisions of households to adopt (or not) either wireline or wireless service.

4.1   Bivariate Probit Model

We begin with a simple specification of household decisions to adopt (or not) wireline service and, potentially independently, adopt (or not) wireless service. The results of two probit regressions are reported in Model (a) of Table 3. The first regression estimates households' decisions to adopt wireline service, and the second regression estimates households' decisions to adopt wireless service. The key assumption underlying these probit estimations

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[33]To test the validity of this assumption, we examined data in the 2003 Annual Report and Analysis of Competitive Market Conditions With Respect to Commercial Mobile Services published by the Federal Communications Commission. This report examines,*inter alia*, geographic patterns of wireless deployment in the United States. It presents data that mobile coverage, while not abundant with carriers in 2002, was geographically widespread.

is that the decisions to adopt wireline service and wireless service are unrelated. To test this proposition, we allow for the possibility that the error structures across these equations are related.[34] We subsequently estimate a bivariate probit model which yokes the decision to adopt (or not) wireline and wireless services, respectively, by accounting for common correlation (ρ) between the error structure in the two equations.[35] The estimation results are shown in Model (b) of Table 3, and reveal a strong negative correlation ($\rho = -.52$) in the error structure from the two equations that is significantly different from zero ($p = .01$). The hypothesis of independence of these decisions is therefore strongly rejected. The negative and statistically significant correlation indicates that positive random errors to the wireless subscription equation are associated with negative random errors to the wireline subscription equation. Because this association is, by construction, through the error structure no causality can be inferred. Moreover, as demonstrated by Miravete and Pernias (2010) any inferences regarding the substitutability or complementarity of the services based on correlations of the error terms is inapt. The results nevertheless strongly reject the hypothesis that these decisions are made independently, indicating that the bivariate model is prefered to the estimation of two independent probit equations.

To address the endogeneity issues mentioned above we implement Rivers and Vuong's (1988) two-stage conditional maximum likelihood (2SCML) estimation of the probit and bivariate probit models. In our case, the models are estimated using the following system of equations:

$$y_{it} = \sum_{j=N,W} \beta_j Price_{ijt} + \gamma_k X_{it} + \gamma_m Z_{ijt} + \epsilon_{it}, \tag{5}$$

$$\tilde{y}_{it} = \sum_{j=N,W} \kappa_j Price_{ijt} + \xi_k X_{it} + \xi_m Z_{ijt} + \tilde{\epsilon}_{it}, \tag{6}$$

where y_{it} and $\tilde{y}_{it}$ are dummy variables which equal to 1 if a household is subscribed to wireline (respectively, wireless) service at time t. $Price_{ijt}$ is the price faced by household i for service j at time t, X_{it} is an $k \times 1$ vector of demographic and nodal characteristics of household i in year t; Z_{ijt} is an $m \times 1$ vector of quality variables for household i for telephone option j ($j = N, W$) in year t and ϵ_{it} and $\tilde{\epsilon}_{it}$ are error terms.

Allowing for the potential endogeneity of $Price_{ijt}$, we first estimate

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[34]See Greene (2012), p. 738.

[35]For an earlier application of the bivariate approach, see Augereau, Greenstein, Rysman (2006) who model Internet Service Providers' propensities to offer 56K service by utilizing an "X2" modem, a Flex modem, both or neither.

$$Price_{ijt} = \tau_k X_{it} + \tau_m Z'_{ijt} + v_{ijt}, \tag{7}$$

and recover the estimated residuals $\hat{v}_{ijt}$ from equation (12). This in turn allows us to estimate

$$y^\star_{it} = \sum_{j=N,W} \beta_j Price_{ijt} + \gamma_k X_{it} + \gamma_m Z_{ijt} + \sum_{j=N,W} \omega_j \hat{v}_{ijt} + \epsilon'_{it}, \tag{8}$$

$$\tilde{y}^\star_{it} = \sum_{j=N,W} \kappa_j Price_{ijt} + \xi_k X_{it} + \xi_m Z_{ijt} + \sum_{j=N,W} \theta_j \hat{v}_{ijt} + \tilde{\epsilon}'_{it}, \tag{9}$$

where Z'_{ijt} is an $(m+2) \times 1$ matrix which includes Z_{ijt} and two exclusion restrictions (*Telecommunications Wages, Mobile Penetration*).[36] Here $\beta_j, \omega_j, \kappa_j, \theta_j, j = N, W$ are parameters to be estimated, and τ_k, τ_m, γ_k, γ_m, ξ_k and ξ_m are vectors of parameters to be estimated. We assume that both $(X_{it}, Z'_{ijt}, \epsilon'_{it}, v_{ijt})$ and $(X_{it}, Z'_{ijt}, \tilde{\epsilon}'_{it}, v_{ijt})$ are i.i.d; $(v_{ijt}, \epsilon'_{it})$ and $(v_{ijt}, \tilde{\epsilon}'_{it})$ conditional on X_{it} and Z'_{ijt} have joint normal distributions with mean zero and finite positive definite covariance matrices.

In this case

$$y_{it} = \begin{cases} 1, & \text{if } y^\star_{it} > c, \\ 0, & \text{otherwise}, \end{cases} \tag{10}$$

and

$$\tilde{y}_{it} = \begin{cases} 1, & \text{if } \tilde{y}_{it}{}^\star > \tilde{c}, \\ 0, & \text{otherwise}, \end{cases} \tag{11}$$

where c and $\tilde{c}$ represent critical cutoff values that trigger household decisions to subscribe to wireline or wireless service, respectively.

For the bivariate probit model we allow correlation between ϵ'_{it} and $\tilde{\epsilon}'_{it}$ in the second step.

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[36]Our exclusion restrictions seek to capture observable variables that may drive prices but which are not drawn from the demand side. Accordingly, we draw upon measures designed to capture cost variations (and hence indirectly prices) including a measure of telecommunications wages that varies by state and year and a measure of the density of mobile penetration by Economic Area which also varies by year.

That is,

$$\left(\begin{array}{c} \epsilon_{it}' \\ \tilde{\epsilon}_{it}' \end{array} \middle| Price_{ijt}, X_{it}, Z_{ijt}' \right) \sim N \left[\left(\begin{array}{c} 0 \\ 0 \end{array} \right), \left(\begin{array}{cc} 1 & \rho \\ \rho & 1 \end{array} \right) \right], \tag{12}$$

where ρ captures the correlation in the errors across equations (13) and (14). The resulting estimates are consistent and asymptotically normally distributed. Our asymptotic covariance matrix of the 2SCML estimator is based on Rivers and Vuong (1988).[37]

After incorporating the interdependence of the wireline and wireless service subscription choice and accounting for endogeneity, the bivariate probit model performs quite well as shown in Table 3, Model (b). A comparison of the portfolio choices predicted by the model and those actually chosen indicates a good fit. The model correctly predicts 68 and 97 percent of households' portfolio decisions in the wireline and wireless equations, respectively. The specific parameter estimates also provide insight into the determinants of households' portfolio choices for telephony service. The nodal variables provide strong support for the concepts advanced in Section 2 above. In particular, households that are more closely attached to their domicile (node) are more likely to subscribe to wireline service and less likely to subscribe to wireless service. For example, households with a retired household member are significantly more likely to subscribe to wireline service and significantly less likely to subscribe to a wireless service. Other age-related variables that characterize household members (e.g., *Young Household* and *Young-Middle Household*) similarly reflect the greater propensity of younger and more mobile households to subscribe to wireless service, and the corresponding decrease in the propensity of these households to subscribe to wireline telephone service.

Households with different levels of work-related attachments are found to be attracted differentially to wireline and wireless services. In particular, *Ratio Working* increases the propensity to subscribe to wireless telephony and decreases the propensity to subscribe to wireline telephony. Households in which a member works part-time (*Part-Time Employed*) are more likely to subscribe to both wireline and wireless service, in comparison to other households. Households with a self-reported *Housewife* appear more more likely to subscribe to wireline service and less likely to subscribe to wireless service, though these results are statistically insignificant.

Households with a health-limited youth (*Limited Youth*) are no different than other house-

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[37]See, in particular, Rivers and Vuong (1988) equations 4.7 and 4.11. Matrices incompatibility prohibits computation of the covariance matrix for recursive bivariate probit model, discussed below, which includes an additional explanatory variable. Nevertheless we provided estimation results from the second step and these are largely consistent with those obtained in the other estimations.

holds in their propensity to subscribe to wireline service, but as anticipated are significantly more likely to subscribe to wireless service than other households. By contrast, households with a health-limited adult (*Limited Adult*) are more likely to subscribe to wireline services and less likely to subscribe to wireless services than other households. Households with students (*Student*) have significantly higher propensities to subscribe to wireless telephony and have significantly lower propensities to subscribe to wireline service. The estimations also reveal that, *ceteris paribus*, households in more rural areas have higher demands for wireless services in comparison to households in more urban areas. Finally, the estimations indicate that home ownership (*Own House*) is strongly associated with subscription to both wireline service and wireless service.

The price and income parameters are also revealing. Consistent with standard demand theory, *Wireline Price* and *Wireless Price* negatively [and statistically significantly *(p = .01)*] impact the demand for wireline and wireless service, respectively.[38] Beyond the own-price impact, however, the estimations also reveal that the cross-price effects are positive and highly statistically significant. Changes in the price of wireline service positively impact the demand for wireless service, while changes in the price of wireless services positively affect the propensity to subscribe to wireline service. The estimations indicate that consumers view wireline and wireless telephone subscriptions as substitutes. While the nonlinear nature of the estimations prevents simple interpretations of marginal effects (ME), they are estimable.[39] Specifically, recalling that $Q_n = \pi_N + \pi_{NW}$ and $Q_W = \pi_W + \pi_{NW}$, we estimate the marginal price effects $\frac{\partial Q_N}{\partial P_N}$, $\frac{\partial Q_W}{\partial P_W}$, $\frac{\partial Q_N}{\partial P_W}$ and $\frac{\partial Q_W}{\partial P_N}$. The results are presented in Table 4, and indicate that the own-service marginal effects are both negative and statistically significant *(p=.01)*, while the cross-partial derivatives are both positive and highly significant *(p=.01)*.[40] From equation (9), this latter result again indicates that wireline and wireless services display substitutable rather than complementary characteristics over the 2003-2010 period.

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[38]To account for the potential for heterogeneous responses of consumers across income and age categories, we alternatively included price interacted with income category and price interacted with age category. In some instances we found that younger people are less price-sensitive to the price of mobile service in the mobile equation. Estimates also provide modest indications that younger people are more price-sensitive with respect to the price of wireline service. We also find that lower income households are generally more price-sensitive than higher income households. Given the broad income and age categorizations, however, these results suffer from collinearity and are somewhat unstable. Accordingly, they are not reported here.

[39]In nonlinear models with single-index form conditional means, marginal effects are calculated using the formula $ME_j = \frac{\partial \pi_j}{\partial x_j} \times \beta_j$. In our case, marginal effects are calculated at mean values of independent variables. For the bivariate probit model, we calculate marginal effects for the following probabilities: $\pi_N, \pi_W, \pi_{NW}, \pi_0, \pi_{W|N}, \pi_{N|W}, \pi_N + \pi_{NW}, \pi_W + \pi_{NW}$. (Cameron and Trivedi (2010)).

[40]Our estimates are conservatively based on the assumption that consumers respond to any price stimulus within a single period. To the extent that consumers fail to fully equilibrate within a single period (due, for example, to the multiyear nature of some wireless contracts) our estimates may be seen as a lower bound on the true marginal effects.

Table 4 indicates that *Income* is an important determinant to wireline and wireless subscription. In each case, income increments for those below the poverty threshold to higher levels increase subscription to both wireline and wireless services. The marginal effect of an income shift from the lowest to the highest category results in about a six percent increase in the likelihood of wireline service subscription *(p=.01)* and about a 26 percent increase in the likelihood of wireless service subscription *(p=.01)*.

The quality and diffusion of wireless service are also found to affect consumers' telephony portfolio decisions. *Cellsites* is positive and highly significant *(p=.01)*, indicating as expected that quality improvements associated with greater coverage increases wireless telephony subscription. The *Cellsites* variable also captures the potential network effect of the impact of the increasing proliferation of the network on the likelihood that any household i will subscribe to wireless service.[41] Similarly, the diffusion of wireline broadband (*Wireline Broadband*) is seen to have enhanced the propensity to retain wireline telephone service and stem the move to wireless service. Finally, areas with more challenging topographies, such as mountains or large bodies of water, which reduce wireless service quality are found to reduce wireless subscription.

Among the most substantial changes in households' telephony portfolio over the 2003-2010 period, the shift away from "wireline-only" is arguably the most dramatic. As Figure 1 indicates, approximately 50 percent of all U.S. households subscribed exclusively to wireline telephony in 2003. That percentage had fallen to 12 percent by 2010. To explore this phenomena in more detail, we bifurcate the sample into an early period (2003-2006) and a later period (2007-2010).[42] Specifically, we decompose the aggregate marginal effects: $-\frac{\partial \pi_N}{\partial P_N} = \frac{\partial \pi_W}{\partial P_N} + \frac{\partial \pi_{NW}}{\partial P_N} + \frac{\partial \pi_0}{\partial P_N}$, permitting us to see how the marginal reaction of consumers to relative prices has evolved over time. Table 5 shows the decomposition results of the total marginal substitution effect associated with a change in the price of wireline service. In the 2003-2006 period, there is relatively moderate substitution directly away from wireline services. During this period, only about one-half of the marginal substitution from wireline-only customers was the result of households becoming wireless-only, with the other half seemingly trying out wireless telephony but not dropping their wireline service. By the 2007-2010 period, however, the marginal impact on wireline only households was largely toward a wireless-only portfolio choice. That is, the dominant marginal effect to any elevation of wireline prices in the later period was for households to "cut the cord" and go wireless-only.

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[41]The geographic scope of any network effect is difficult to bound conceptually. Accordingly, in an alternative estimation we employed a more narrow geographic measure of the potential for network effects by including a measure of the extent of wireless subscription in the county in which the household is located. This approach, which parrots Goolsbee and Klenow (2002), yields similar results to those reported here.

[42]We find similar patterns emerge if alternative years are chosen for this bifurcation.

4.2 Mixed Logit Model

To this point, we have permitted households' decisions to adopt wireless and wireline telephony to be related, but not part of a single household decision-making process. To allow for this possibility, we utilize a mixed logit model. This model accounts for heterogeneity in consumers' preferences and relaxes the assumption of the independence of error terms in the utility specification, unlike a multinomial logit model. In our model we allow the price coefficient to vary randomly across consumers. We specify the price coefficient to be independently normally distributed. We also account for potential endogeneity of the prices.

A consumer faces four alternatives for a telephone: (1) no phone, (2) wireline only, (3) wireless only, or (4) both wireline and wireless, and chooses the alternative with the highest level of utility. The utility of option j ($j = N, W, NW$), which accordingly corresponds to the choice of wireline only (N), wireless only (W), or both phones (NW) can be written as:

$$U_{ijt} = V(Price_{ijt}, X_{it}, Z_{ijt}, \beta_i) + \epsilon_{ijt}, \tag{13}$$

where all variables have the same notation as described above in the Bivariate Probit Model section, β_i is a random price coefficient that represents taste of consumer i, and ϵ_{ijt} is the unobserved portion of utility.

To address the issue of potential endogeneity of prices, we follow Petrin and Train (2010), implementing a control function approach. The idea behind the control function approach is to derive proxy variables that condition on the parts of endogenous variables that are correlated with the unobserved utility ϵ_{ijt}. This approach can be implemented if the endogenous variables are regressed on all the exogenous variables that enter utility and some variables Y that do not directly enter utility, but which do impact the endogenous variables (these variables are called exclusion restrictions).

The control function approach is conducted in two stages. In the first stage, OLS regression of prices (wireline and wireless) on the exogenous explanatory variables and exclusion restrictions is implemented:

$$Price_{ijt} = f(X_{it}, Z'_{ijt}, Y_{ijt}) + v_{ijt}. \tag{14}$$

Then we recover the estimated residuals to use them as control functions in the estimation of mixed logit in the second stage.

$$\epsilon_{ijt} = CF(v_{ijt}; \lambda) + \tilde{\epsilon}_{ijt}, \tag{15}$$

where λ is the corresponding 3×1 vector of parameter of the control function. We specify the control function (CF) as linear in v_{ijt}; $\tilde{\epsilon}_{njt}$ are i.i.d. extreme value and independent of other regressors.

The utility function with the control function that generates the mixed logit model is specified as:

$$U_{ijt} = V(Price_{ijt}, X_{it}, Z_{ijt}, \beta_i) + \lambda v_{ijt} + \sigma \eta_{ij} + \tilde{\epsilon}_{ijt}, \tag{16}$$

where η_{ij} is i.i.d. standard normal. The model is a mixed logit, with mixing over the error components η_{ij}, whose standard deviation σ is estimated, as well as over the random elements of β_i.

Conditional of the CF, the probability that consumer i chooses alternative s is equal to

$$P_{is} = 1(U_{ist} > U_{ijt} \forall j \neq i) f(\beta_i, \tilde{\epsilon}_i) \phi(\eta_i) d\beta_i d\tilde{\epsilon}_i d\eta_i \tag{17}$$

Given that the error terms follow extreme value distribution, the mixed logit probability based on this utility is

$$P_{is} = \int \left(\frac{e^{V_{is}(v_i, \nu_i, \eta_i)}}{\sum_{j=1}^4 e^{V_{ij}(v_i, \nu_i, \eta_i)}} \right) \phi(v_i) \phi(\nu_i) \phi(\eta_i) dv_i d\nu_i d\eta_i. \tag{18}$$

Table 6 provides the results of the Mixed Logit model, which are similar to those provided in the Bivariate Probit estimation of Table 3. The importance of both the household's nodal propensities as well as price and income are confirmed. The price that households face for their respective portfolio choice is negative and highly statistically significant, indicating that consumers are price sensitive across the various options as they consider their portfolio of telephone services. Consumers from the lowest income category are the most price sensitive. Similarly, the nodal variable parameter estimates from the Mixed Logit model are quite similar in nature to those generated in the Bivariate Probit model, providing reassuring robustness.

5   Conclusion

The introduction of new products or services with new technologies and characteristics presents a number of challenges to traditional demand analysis. Faced with this situation, consumers may replace or augment their existing consumption portfolios. In particular, the new product or service may serve as either a substitute or complement to the existing product or service. In this regard, the advent and diffusion of wireless telecommunications has radically altered traditional consumption patterns among consumers, creating a natural opportunity to consider telecommunications demand with a portfolio choice lens.

In this paper, we develop an economic framework capable of capturing the pattern and evolution of telecommunications consumers' portfolio consumption choices. In doing so, we provide several contributions that may serve as a platform for subsequent research. First, we formulate a portfolio choice framework for how households satisfy their communications needs. Second, within that portfolio choice model, we develop a theory of why (non-price) characteristics of households, especially related to their "nodal" versus mobile tendencies, affect their subsequent telephony portfolio choices. Third, the portfolio choice framework sheds considerable light on the "substitutes versus complements" issue that underpins competition and regulatory policies toward the telecommunications industry. Fourth, given our data window from 2003-2010, we are able to observe empirically how variations in the quality and ubiquity of the "new service" affects consumers' portfolio choices.

The empirical results provide considerable support for the approach that we have adopted. In particular, we find that variations in households' nodal characteristics serve as important drivers their portfolio choices of telephone service. Households that are more closely attached to their domiciles are more attracted toward wireline service, while households with more mobile lifestyles are more attracted to wireless telephony. The results also consistently and robustly reveal that wireline and wireless services have increasingly become substitutes. Variations in the quality and ubiquity of wireless telephony are found to be important determinants of wireless telephony subscription growth relative to wireline telephony over the 2003-2010 period.

Finally, our results may prove useful in a policy domain. At the most general level, our approach here may be seen as a platform for tracking the evolution of consumer responses to the emergence of new technologies. Understanding such responsiveness is crucial in the design of regulatory and competition policies. And, specifically, in its considerations of the appropriate level of regulation for wireline telephone services, the Federal Communications Commission has indicated that the issue of access substitution between wireline and wireless services is "critical" and a "difficult question."[43] While our study is generally directed at

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[43]See Memorandum and Order, In the Matter of Petition of Qwest Corporation for Forbearance Pursuant

the more basic questions of the economic drivers of households' telephony portfolio choices, our results provide clear and robust indications of the access substitutability of wireline and wireless services. This substitutability indicates that regulatory policies designed that silo wireline and wireless services are no longer apt.

While advancing our understanding of households' portfolio choices, our research points toward next steps that hold the potential to paint a more complete picture of economic outcomes in the telecommunications industry. For example, our focus has been on the demand side of the evolving industry. By specifying and estimating a stylized supply-side model it may be possible to extend our results in several ways. For instance, with an appropriate specification of the supply side both the social welfare effects of the adoption of wireless services and the atrophying traditional fixed-line services could be evaluated. Also, by using knowledge of the cost structure it may be possible to conduct counter-factual simulations that could include, for instance, an examination of what pricing in wireline/wireless services would be in the absence of the other service. Additionally, such a more complete model would permit an identification of optimal pricing as done by Gentzkow (2007) in the provision of online and print newspapers. Our analysis here has also abstracted from a salient feature of the market for wireless telephony services; namely the durability of the hardware and consumer switching costs associated with early termination of wireless contacts. This suggests that subsequent research that considers intertemporal optimization in individual consumer decisions may provide substantial additional insights not afforded by our approach.

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to 47 U.S.C. Section 160(c) in the Phoenix Metropolitan Area, WC Docket No. 09-135, Federal Communications Commission, p. 30.